Australian Government
Department of Defence
Defence Science and
Technology Organisation

Structural Stability Assessment of the High Frequency Antenna for Use on the Buccaneer CubeSat in Low Earth Orbit

Iain Cartwright

National Security Intelligence Surveillance and Reconnaissance Division
Defence Science and Technology Organisation

DSTO-TN-1295

ABSTRACT

The Buccaneer CubeSat will be fitted with a high frequency antenna made from spring steel measuring tape. The geometry of the antenna is described as open bowtie. In the microgravity of low Earth orbit there is a risk that the antenna will collapse or bend due to the extremely small loads. Worst case empirical analysis has shown that the antenna will remain deployed in low Earth orbit. This has been shown in the presence of worst case environmental loads due to aerodynamic drag (at 300 km) and solar radiation pressure, combined with peak rotational accelerations. The high frequency open bowtie antenna will have a margin of safety of at least 54.8.

RELEASE LIMITATION

Published by

National Security Intelligence Surveillance and Reconnaissance Division
DSTO Defence Science and Technology Organisation
PO Box 1500
Edinburgh South Australia 5111 Australia

Telephone: 1300 333 362
Fax: (08) 7389 6567

AR-015-942
May 2014

APPROVED FOR PUBLIC RELEASE

Structural Stability Assessment of the High Frequency Antenna for Use on the Buccaneer CubeSat in Low Earth Orbit

Executive Summary

The Buccaneer CubeSat will be fitted with a high frequency antenna made from commercially available spring steel measuring tape. The antenna is very large when compared to the CubeSat, around 10 times the satellite length, the antenna cannot support its own weight on the surface of the Earth. The spring steel tape is very thin and flexible there is a risk that the antenna might collapse in the presence of the loads in low Earth orbit.

This assessment of the antenna's margin of safety will treat it as a cantilever beam under bending. The failure mode under consideration is buckling. If the antenna was to fail, this would be an elastic failure and the antenna would self-restore when the loads subside. The bending moments shall be calculated at the point where the antenna attaches to the body. If the maximum possible bending moment is less than the failure bending moment, the antenna will remain deployed. This assessment was conducted with the following worst case condition:

- if the satellite was in orbit at an altitude of 300 km
- during a solar maximum
- Magnetorquers are developing their maximum possible torque.

In all cases the loads will not be sufficient to cause the antenna to crease and fail about the antenna to body attachment point. Therefore there can be confidence that the high frequency open bowtie antenna will remain deployed in low Earth orbit. The high frequency open bowtie antenna will have a margin of safety of at least 54.8.

Observations of the antenna release mechanism experiment are also included, these have shown that there will be no risk to the overall satellite, and the residual rotational motion will be small.

The use of spring steel presents a low risk solution in terms of deployment and stability once deployed for use in low Earth orbit.

This page is intentionally blank

Contents

This page is intentionally blank

1. Introduction

The Buccaneer satellite is a 3U CubeSat with the body dimensions 0.34 m x 0.1 m x 0.1 m with a total mass of up to 4 kg. These dimensions are in accordance with the CubeSat design specifications (Cal Poly 2009). The payload on-board Buccaneer is a high frequency receiver. The mission will provide performance calibration of some aspects of the Jindalee Over-the-Horizon Radar Network (JORN). The corresponding antenna is large when compared to the satellite as is shown in Figure 1. The antenna will be stowed during launch and jettison from the launch vehicle. Once the spacecraft is operating the antenna sections will be deployed. Each section measures 1.73 m from body to tip or 3.46 m from tip to tip. The antenna will be constructed using commercially available spring steel measuring tape. The spring steel tape is very thin and flexible, but in the microgravity of low Earth orbit with extremely small loads it is anticipated the antenna will remain stable once it is deployed. The following assessment has been conducted to understand the design margin.

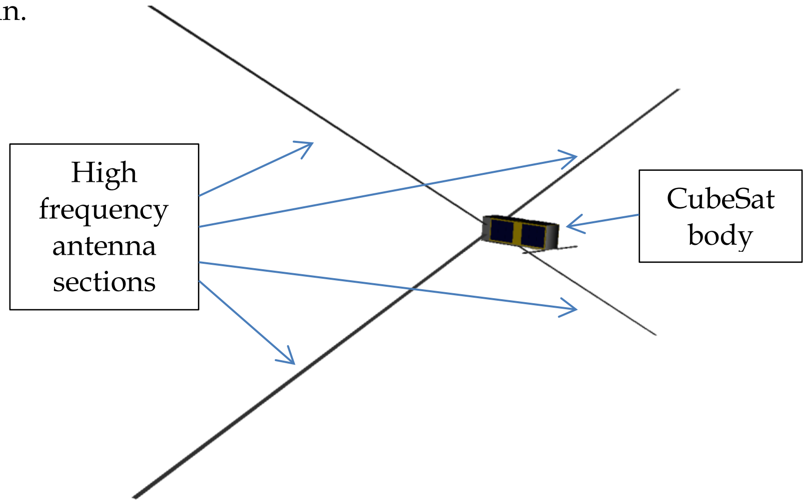


Figure 1 Buccaneer CubeSat with open bowtie high frequency antenna on aft face

This assessment of the antenna's margin of safety will treat it as a cantilever beam under bending. The failure mode under consideration is buckling. If the antenna was to fail, this would be an elastic failure and the antenna would self-restore when the loads subside. The bending moments shall be calculated at the point where the antenna attaches to the body. If the maximum possible bending moment is less than the failure bending moment, the antenna will remain deployed. The antenna will be subjected to the following loads perpendicular to its length that will contribute towards bending moments:

1. aerodynamic (due to the extremely low density rarefied atmosphere)
2. Solar Radiation Pressure (SRP) (due to photons striking the antenna)
3. inertial loads (due to any rotational accelerations).

The deployment of the antenna is dramatic as the elastic strain energy is released, observations have been made of the antenna deployment and a brief discussion of the negligible impact to the satellite is also discussed.

2. Experimental derivation of the buckling strength

The spring steel tape selected for the antenna is Stanley 30-497 measuring tape. The tape is available in spools of 5 m, and a maximum section length of 1.73 m is required. The tape has a flattened width of 19 mm, a broad cross-section of 18mm and a narrow cross-section of 2.5 mm. The tape is 0.1mm thick. Segments with rivets will not be used for the antenna as shown at the end of the tape in Figure 2. The antenna will be in a stable equilibrium position once it is deployed, utilising the manufactured curvature of the measuring tape to provide stiffness.

Figure 2 Stanley 30-497 measuring tape

The mass of two lengths of tape were measured to determine the mass per unit length required for later calculations these were found to be 0.0156 kg/0.898 m = 0.0174 kg/m and 0.0832 kg/4.98 m = 0.0167 kg/m. 0.0167 kg/m shall be selected as a smaller value and therefore smaller failure bending moment will be most conservative.

The manufactured curvature of the tape is supported by the clamp at the attachment point as shown in Figure 3. Both the concave and convex components of the clamp are used in the following method.

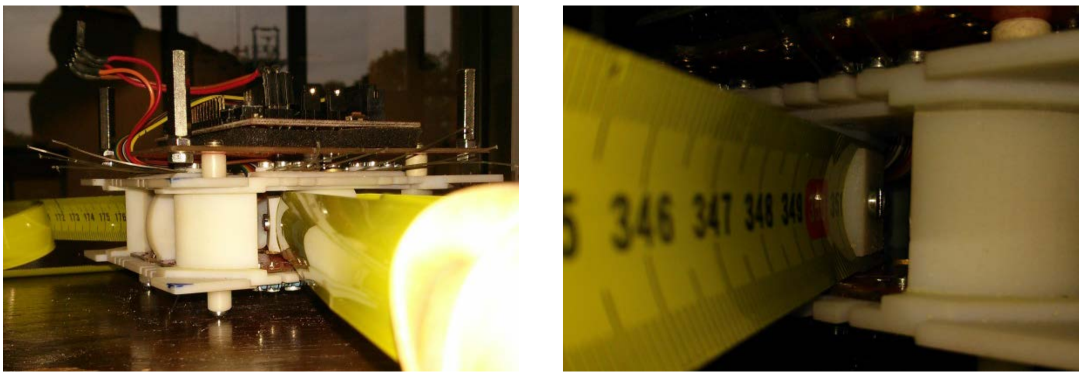


Figure 3 Antenna body attachment point

As shown in Figure 4 the tape was passed over the table edge (1) until the point when it collapsed under its own weight (2). Following this the tape overhang was reduced until it restored (3) to a straight configuration. The tape was supported and held by both sections of the clamp but not pinned so it could be slid through the clamp during the experiment. This ensured the profile was the same as shown in Figure 3.

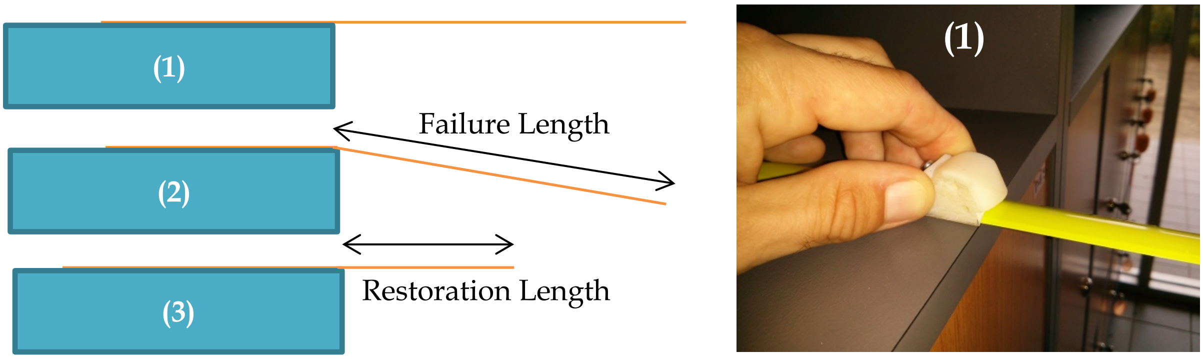


Figure 4 Experimental test configuration

The experiment was conducted with the tape held in various orientations shown in Figure 5. The arrows indicate the downwards direction with respect to the manufactured curved cross-section of the tape.

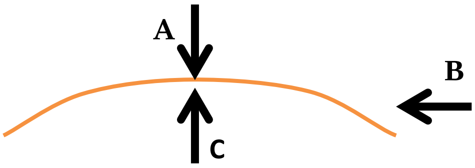


Figure 5 Tape orientations view along tape length (into the curved cross-section)

The experiment was repeated three times for each orientation, a summary of the results of the minimum lengths for each orientation is shown in Table 1. The tape would notably bend downwards and twist a small amount before collapsing. The bent configuration immediately before buckling was stable and could be held indefinitely.

Table 1 Minimum Antenna failure and restoring lengths

Direction	Failure Length	Restoration Length
A	750 mm	510 mm
B	780 mm	740 mm
C	1750 mm	620 mm

The minimum length is the weakest and hence worst case. It should be noted that when other orientations between A, B and or C were attempted the restoration lengths were always greater than found for length A. The restoration length for direction A will be used to calculate the failure bending moment. The failure bending moment is defined as:

$$(1) \qquad M_{Fail} = m_{Unit\ Length} \cdot g \cdot \frac{L_{Fail}{}^2}{2} = 0.0167 \left(\frac{kg}{m}\right) \cdot 9.807 \left(\frac{m}{s^2}\right) \cdot \frac{(0.51(m))^2}{2} = 2.13 \times 10^{-2}\ (Nm)$$

Where g is the acceleration due to gravity.

3. Assumptions of Loads

The loads included in this assessment will be limited to the three listed above. Torsion on the antenna will not be considered. The calculation of buckling instability loads is unnecessary as no significant loads will act along the antenna length towards or away from the satellite body.

The tape is extremely thin measuring only 0.1 mm in thickness, hence even in the harsh thermal environment of space the antenna is expected to act as an isothermal node. The negligible temperature differential through the antenna will result in negligible thermal strain hence this will not be considered. A large number of satellite and even inter planetary missions have used spring steel measuring tapes as their antennas, this heritage provides confidence in its use as a suitable lightweight and high packing efficient material.

4. Environmental Loads

When the satellite is in orbit, extremely small loads will be present on its external surfaces. The loads are due to aerodynamic and SRP force. It is necessary to calculate the force and resulting bending moment that could lead to the antenna buckling. The loads are calculated as follows:

$$F_{Aero} = \frac{1}{2} \cdot c_d \cdot \rho \cdot A \cdot V^2 \quad (2)$$ (Eq 9-30, Wertz 2011)

$$F_{SRP} = \frac{\Phi}{c} \cdot A \cdot (1 + q) \quad (3)$$ (Eq 19-5, Wertz 2011)

$$A = L \cdot W \quad (4)$$

Where:

c_d	2.2	Drag coefficient (typical value (Wertz 2011))
ρ	4.39×10^{-11} to 3.08×10^{-13} kg/m^3	Maximum atmospheric density (300km to 650km altitude (Wertz 2011))
L	1.73 m	Antenna length
W	0.018 m	Antenna width
A	0.0311 m^2	Area of the antenna, normal to direction A shown in Figure 5
V	7.73×10^3 to 7.53×10^3 m/s	Velocity normal to area (300km to 650km altitude)
Φ	1393 W/m^2	Solar constant
c	2.98×10^8 m/s	Speed of light
q	0.5	Unitless reflection factor

There is an assumption that any counteracting bending moment due to loads acting on the body are negligible when compared with the bending moment due to loads on the antenna. This is a conservative assumption.

As aerodynamic load is a function of density and velocity it will vary with respect to altitude. Lower altitudes result in increased density and increased velocity to maintain a circular orbit. It should be noted that at the extremely low densities expected in low Earth orbit, low speed aerodynamic effects such as vortex shedding or high speed shockwaves are not relevant.

5. Environmental Bending moments

The antenna sections from attachment point to tip will be modelled as a cantilever beam. The environmental loads due to aerodynamic drag and SRP will be modelled as uniformly distributed loads. The maximum bending moment will be experienced at the fixed hinge end. The bending moment is given by:

$$M = \frac{F \cdot L}{2} \tag{5}$$

This results in the following equations for bending moments resulting from aerodynamic (6) and SRP (7) forces.

$$M_{Aero} = \frac{1}{4} \cdot c_d \cdot \rho \cdot V^2 \cdot W \cdot L^2 \tag{6}$$

$$M_{SRP} = \frac{\Phi}{c} \cdot (1 + q) \cdot W \cdot \frac{L^2}{2} \tag{7}$$

Hence the total worst case bending moment at 300km is calculated as follows:

$$M_{Env} = M_{Aero} + M_{SRP} = 7.764 \times 10^{-5} + 1.877 \times 10^{-7} = 7.783 \times 10^{-5}\ (Nm) \tag{8}$$

Figure 6 shows the variation of bending moment with respect to altitude. The bending moment due to aerodynamic drag is significantly greater than the bending moment due to SRP. The altitude independent bending moment due to SRP is 1.877×10^{-7} Nm. At 300 km, the worst case aerodynamic bending moment is 7.764×10^{-5} Nm. These worst case conditions have been calculated by considering the forces acting perpendicular to the widest face of the antenna.

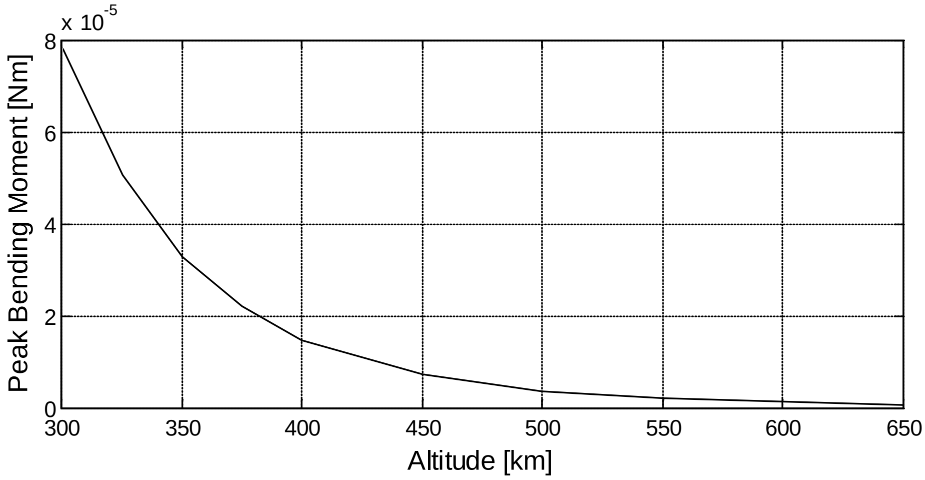


Figure 6: Worst case bending moment for various altitudes

The corresponding margin of safety based on a safety factor for buckling of 1.3 is calculated as follows:

(9) $$MS = \frac{M_{Fail}}{SF_{Buckling} \cdot M_{Env}} - 1 = \frac{2.13 \times 10^{-2}}{1.3 \cdot 7.783 \times 10^{-5}} - 1 = 209.6$$

The Buccaneer mission will be launched into an orbit with a perigee greater than 300 km. At this altitude the bending moment due to environmental loads will have a margin of safety of 209.6. The density values used in this assessment were obtained from Space Mission Engineering textbook (Table L-1 Wertz 2011). The worst case (largest) values were used that might be expected during a solar maximum, this is when sun spot number and solar activity reach a maximum exciting the Earth upper atmosphere (Thermosphere).

6. Inertial loads

As the antenna and the satellite are subject to the same gravitational field each element of the satellite will accelerate as one. If the orbit is not perfectly circular any acceleration felt by the body will not be between relative components. It is feasible that Buccaneer will utilise an angular moment exchange device such as a reaction or momentum wheel to provide attitude stability and control. The bending moment that would be generated by such a device will generate body rotational accelerations that will lead to a bending moment at the hinge of the antenna and the satellite body.

The dynamical situation of the rotating satellite and antenna can be resolved to a static one by applying D'Alembert's principle, in which forces to accelerate masses are replaced by equal and opposite static forces (Benham 1976).

The inertial load due to rotational acceleration will be represented at a linearly increasing load from hinge to tip.

(10) $$Q(x) = \frac{\alpha \cdot m_{Unit\ Length}}{2} \cdot x^2$$

Where:

$Q(x)$		Accumulated load at the fixed end.
$m_{Unit\ Length}$	0.0174 kg/m	Mass per unit length
x		Distance from fixed end

7. Inertial bending moments

The antenna section from hinge to tip will be modelled as a cantilever beam. The maximum bending moment resulting from the linearly increasing load will be experienced at the fixed hinge end.

Thus the bending moment at the antenna attachment point will be:

$$M_{Int} = SF_{SpringBack} \cdot \alpha \cdot m_{Unit\ Length} \cdot \frac{L^3}{3} \tag{11}$$

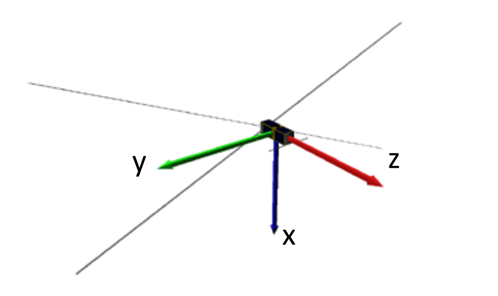
Where:

$SF_{SpringBack}$	A safety factor of 2.0 to accommodate for the spring back of the antenna.
α	Angular acceleration of the tape.
L	Length of the tape.

The analysis of the Buccaneer spacecraft has, prior to this study, assumed the spacecraft to be a rigid body, but this is not realistic. If the satellite body began to rotate, but each section of tape remained stationary the tape attachment point would behave like a pinned joint and crease as it is unable to transfer bending moment. Rotational acceleration would reach a maximum if the peak bending moment from a reaction or momentum wheel (if the design employed one) was applied through the least inertially stiff axis. As shown in Table 2 the least stiff axis for the satellite body is the Z axis. An additional safety factor of 2.0 has been included to compensate for any spring-back of the antenna during acceleration.

Table 2 Moments of inertia for the standard 3U and Buccaneer satellite configurations

MOI Axis	Satellite Body [kg.m²]	Buccaneer [kg.m²]
I_x	41.3×10^{-3}	143.5×10^{-3}
I_y	41.3×10^{-3}	58.8×10^{-3}
I_z	6.56×10^{-3}	126.5×10^{-3}



The MAI 400 reaction wheels can deliver a maximum torque (T_{Max}) of 0.625×10^{-3} Nm (Maryland Aerospace 2014). The maximum angular acceleration that Magnetorquers could produce is 24.53×10^{-6} Nm (Maryland Aerospace 2014) or 3.9% of the reaction wheels.

At the project preliminary design review held on 28-January-2014 a baseline for Buccaneers control system was established. It is anticipated that Magnetorquers alone will act at the actuators in the attitude control system for Buccaneer.

The resulting angular acceleration is calculated as follows:

$$\alpha = \frac{T_{Max}}{I_z} = \frac{24.53 \times 10^{-6}\ (Nm)}{6.56 \times 10^{-3}\ (kg \cdot m^2)} = 3.74 \times 10^{-3}\ \left(\frac{rad}{s^2}\right) \tag{12}$$

Thus from equation (11), the worst case bending moment at the hinge is due to inertial loads will be:

$$M_{Int} = 2.0 \cdot 3.74 \times 10^{-3}\ \left(\frac{rad}{s^2}\right) \cdot 0.0167\ \left(\frac{kg}{m}\right) \cdot \frac{\left(1.73\ (m)\right)^3}{3} = 2.156 \times 10^{-4}\ (Nm) \tag{13}$$

The corresponding margin of safety based on a safety factor for buckling of 1.3 is:

$$MS = \frac{M_{Fail}}{SF_{Buckling} \cdot M_{Int}} - 1 = \frac{2.13 \times 10^{-2}\ (Nm)}{1.3 \cdot 2.156 \times 10^{-4}\ (Nm)} - 1 = 75.0 \tag{14}$$

The resulting bending moment at this acceleration is 2.156×10^{-4} Nm, which provides a large margin of safety of 75.

8. Combined load case

The worst case environmental loads are considered to act on the broadest side of the antenna. This will result in hinge bending moments about the Z axis. As the worst case inertial loads have also been calculated about the Z axis the loads can be summed using superposition to give the total worst case bending moment this is shown to be:

$$\sum M = M_{Env} + M_{Int} = 7.78 \times 10^{-5}\ (Nm) + 2.156 \times 10^{-4}\ (Nm) = 2.934 \times 10^{-4}\ (Nm) \tag{15}$$

This margin of safety for the combined case based on a safety factor for buckling of 1.3 is calculated as,

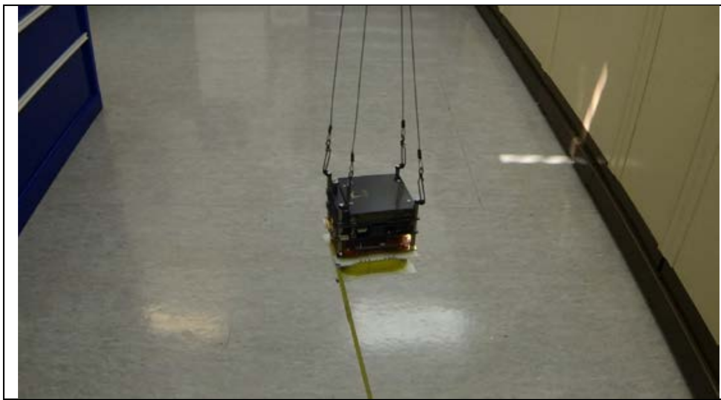
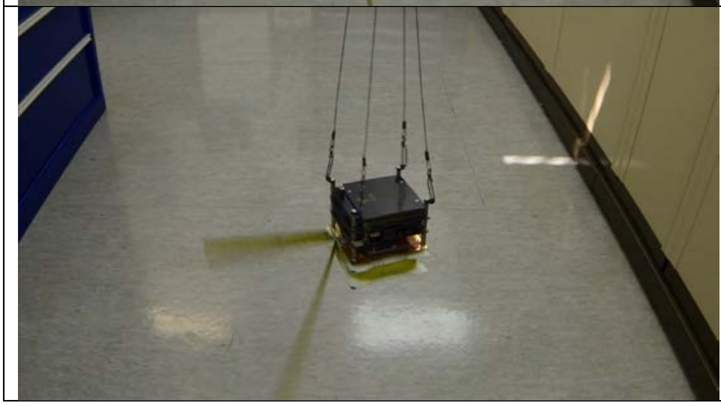
$$MS = \frac{M_{Fail}}{SF_{Buckling} \cdot \sum M} - 1 = \frac{2.13 \times 10^{-2}\ (Nm)}{1.3 \cdot 2.934 \times 10^{-4}\ (Nm)} - 1 = 54.8 \tag{16}$$

giving a margin of safety of 54.8. This is considered large hence the antenna should remain deployed in low Earth Orbit.

9. Antenna Release Experiment

The high frequency antenna utilised on Buccaneer will employ four 1.73 m sections, the deployment mechanism will be a onetime device. The elastic strain energy within the tape will be used to perform the deployment of the antenna. The antenna will be secured using burn wires when it is held to the satellite body.

The deployment of the antenna displays highly non-linear behaviour. An experiment was conducted to evaluate what is likely to happen during antenna deployment. The length of antenna that is released can be tailored. The most conservative release length was used in this experiment a quarter of one turn (90 degrees) of antenna wrap. During the experiment the payload release mechanism and power system was hung in a relatively low friction arrangement. When an antenna section is released the following behaviour is observed:

	The antenna and body are stationary.
	The antenna releases and is accelerated which in-turn accelerates the attached body. The stored elastic strain energy is converted into body angular velocity.

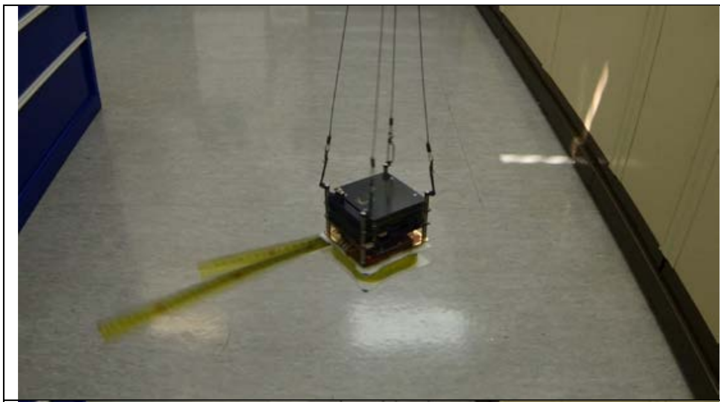
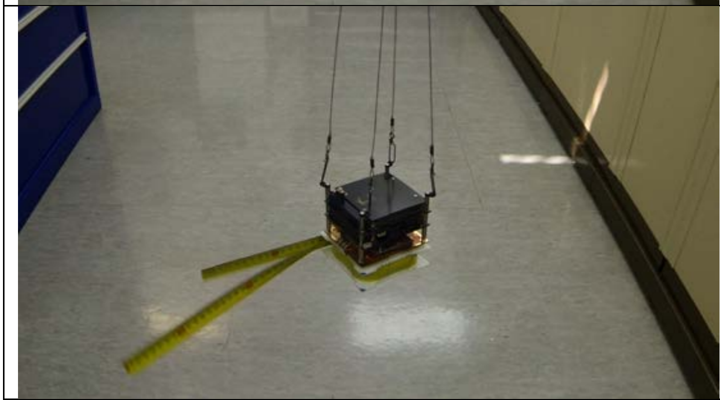
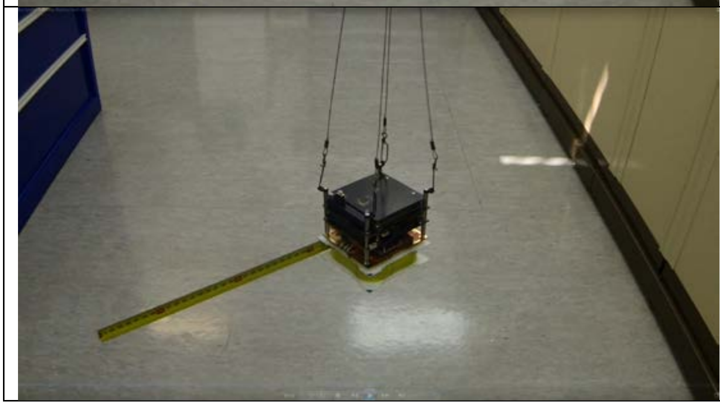
	The antenna section reaches the limit of its free movement, the sudden deceleration of the antenna's motion also halts the body, via a highly non-linear process the angular velocity of the antenna and the body cancel.
	The antenna continues to oscillate and the different length sections can be seen to separate from each other.
	After the oscillations stop the antenna and body has a small rotational velocity. The body has stepped in angle by about 1/8th of a turn. The rotational step of the body appears to be a function of total release length and body inertia.

Figure 7: Antenna deployment experiment still images and descriptions

These observations show that other than an abrupt change in angular position and some residual motion, the release of the antenna is fairly benign and presents no-risk to the satellite.

10. Conclusion

The Buccaneer CubeSat will use a lightweight thin walled antenna constructed from spring steel measuring tape. It is not possible for the antenna to support its own weight on Earth under the presence of 1 g. Once in orbit the antenna will be deployed and there is confidence that it will remain stable for the duration of the mission. If attitude control is achieved using Magnetorquers alone, the margin of safety will be 54.8. This assessment was conducted with the following worst case condition:

- if the satellite was in orbit at an altitude of 300 km
- during a solar maximum
- Magnetorquers or Reaction wheels are developing their maximum possible torque.

In either case the loads will not be sufficient to cause the antenna to crease and fail about the antenna to body attachment point. Therefore there can be confidence that the high frequency open bowtie antenna will remain deployed in low Earth orbit. Experiments of the release mechanism have shown that there will be no risk to the overall satellite, and the residual rotational motion will be small.

At the project preliminary design review held on 28-January-2014 a baseline for Buccaneer's control system was established. It is anticipated that Magnetorquers alone will act as the actuators in the attitude control system for Buccaneer. The extremely small torques developed by Magnetorquers mitigates the risk of dynamic coupling between the control system and the antenna and, or satellite structure. Therefore the margin of safety of 54.8 is appropriate and very large.

11. References

Cal Poly SLO, 2009. CubeSat Design Specification Rev. 12.

P. P. Benham, 1976. *Mechanics of Solids and Structures*. Pitman Publishing.

J. R. Wertz, D. F. Everett, J. J. Puschell, 2011. *Space Mission Engineering: The New SMAD (Space Technology Library, Vol. 28)*. First Edition. Microcosm Press.

Maryland Aerospace Inc, 2014. MAI-400 MiniADACS System Operations Manual. Rev. 1-12-14.

Page classification: UNCLASSIFIED

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION DOCUMENT CONTROL DATA	1. DLM/CAVEAT (OF DOCUMENT)

2. TITLE	3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION)
Structural Stability Assessment of the High Frequency Antenna for Use on the Buccaneer CubeSat in Low Earth Orbit	Document (U) Title (U) Abstract (U)
4. AUTHOR(S)	5. CORPORATE AUTHOR
Iain Cartwright	DSTO Defence Science and Technology Organisation PO Box 1500 Edinburgh South Australia 5111 Australia

6a. DSTO NUMBER	6b. AR NUMBER	6c. TYPE OF REPORT	7. DOCUMENT DATE
DSTO-TN-1295	AR-015-942	Technical Note	May 2014

8. FILE NUMBER	9. TASK NUMBER	10. TASK SPONSOR	11. NO. OF PAGES	12. NO. OF REFERENCES
2013/1242634/1	N/A	DSTO	12	4

13. DSTO Publications Repository	14. RELEASE AUTHORITY
http://dspace.dsto.defence.gov.au/dspace/	Chief, National Security Intelligence Surveillance and Reconnaissance Division

15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT

Approved for Public Release

OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH DOCUMENT EXCHANGE, PO BOX 1500, EDINBURGH, SA 5111

16. DELIBERATE ANNOUNCEMENT

No Limitation

17. CITATION IN OTHER DOCUMENTS Yes

18. DSTO RESEARCH LIBRARY THESAURUS

Antennas, Satellite systems, Satellites

19. ABSTRACT
The Buccaneer CubeSat will be fitted with a high frequency antenna made from spring steel measuring tape. The geometry of the antenna is described as open bowtie. In the microgravity of low Earth orbit there is a risk that the antenna will collapse or bend due to the extremely small loads. Worst case empirical analysis has shown that the antenna will remain deployed in low Earth orbit. This has been shown in the presence of worst case environmental loads due to aerodynamic drag (at 300km) and solar radiation pressure, combined with peak rotational accelerations. The high frequency open bowtie antenna will have a margin of safety of at least 54.8.

Page classification: UNCLASSIFIED